Investigations of Optical Coherence Properties in an Erbium-doped Silicate Fiber for Quantum State Storage

Matthias U. Staudt,[1] Sara R. Hastings-Simon,[1] Mikael Afzelius,[1]
Didier Jaccard,[2] Wolfgang Tittel,[1, 3] and Nicolas Gisin[1]

[1] *Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland*
[2] *Départment de Physique de la Matière Condensée, University of Geneva,*
24 Quai Ernest Anserment, 1211 Geneva 4, Switzerland
[3] *Institute for Quantum Information Science, University of Calgary,*
2500 University Drive, NW Calgary, Alberta, Canada, T2N 1N4
(Dated: February 1, 2008)

We studied optical coherence properties of the 1.53 μm telecommunication transition in an Er^{3+}-doped silicate optical fiber through spectral holeburning and photon echoes. We find decoherence times of up to 3.8 μs at a magnetic field of 2.2 Tesla and a temperature of 150 mK. A strong magnetic-field dependent optical dephasing was observed and is believed to arise from an interaction between the electronic Er^{3+} spin and the magnetic moment of tunneling modes in the glass. Furthermore, we observed fine-structure in the Erbium holeburning spectrum originating from superhyperfine interaction with ^{27}Al host nuclei. Our results show that Er^{3+}-doped silicate fibers are promising material candidates for quantum state storage.

PACS numbers: 03.67.HK; 42.50.Md; 32.70.Jz

I. INTRODUCTION

Optical coherence properties of rare-earth-ion-doped (RE-ion-doped) inorganic crystals have been thoroughly investigated for photon-echo based optical data storage and data processing over several decades[1,2,3]. These materials have interesting low-temperature properties such as small homogeneous linewidths (i. e. long coherence times) and large inhomogeneous broadening (i. e. large frequency bandwidths). Coherent optical control of RE-ions doped into solids has gained further interest in recent years as a result of original proposals in the fast developing fields of quantum communication and quantum computation[4,5,6]. In particular, RE-ions in crystals are promising for the realization of a reversible transfer of quantum states between photons and atoms/ions. Such a quantum memory represents a basic building block for the so-called quantum repeater[7], allowing the extension of quantum communication schemes such as quantum cryptography[8] to very long distances.

An interesting new approach to a memory for quantum as well as for classical light in solid state materials is based on controlled reversible inhomogeneous broadening (CRIB) of a narrow, spectrally isolated absorption line[9,10,11]. One of the major challenges in implementing this protocol is the need for an optically thick atomic medium, with long optical coherence times. The exact requirements for an efficient CRIB based quantum memory are still subject to research, but it seems reasonable to assume that optical depths of a few hundred ($\alpha L > 100$), and coherence times longer than a microsecond will be necessary[12].

However, large optical depths and long coherence times are difficult to obtain simultaneously. Although coherence times longer than a few ms have been observed[13],

these demonstrations normally rely on weakly doped crystals in order to reduce RE ion-ion interactions. Typical absorption coefficients in weakly doped bulk crystals are of the order of 1-10 cm^{-1}. Because interaction lengths are normally limited to a few millimeters, by focusing requirements, the corresponding small optical depths will limit the efficiency of CRIB-based quantum state storage[10].

In this article we investigate the coherence properties of an Er^{3+}-doped silicate fiber at low temperatures, specifically with respect to the requirements for CRIB. This system is promising for the realization of CRIB, as arbitrarily large optical depths can be achieved with low doping concentration through long interaction lengths. Also, the $^4I_{15/2} \rightarrow ^4 I_{13/2}$ transition in Erbium corresponds to a wavelength of 1532 nm (between the two lowest crystal-field levels), thus allowing future interfacing of optical quantum memories with the standard telecommunication fiber networks.

At low temperature, the magnitude and temperature dependence of the homogeneous linewidth differs significantly between RE-ions in amorphous disordered materials and in crystalline hosts. The optical decoherence times are much shorter and quasi-linearly dependent on the temperature. These properties of amorphous systems, for example glasses, are due to coupling between the RE-ion impurity and a broad distribution of low-frequency tunneling modes (two-level systems or TLS), which are normally not present in crystals. Although much research has been done to better understand the low-temperature properties of RE-ion-doped glasses[14,15,16], there are still open questions concerning the exact temperature dependence of the homogeneous linewidth and its origin. In recent photon-echo experiments in a Er^{3+}-doped silicate fiber[17], a new magnetic-field-dependent optical dephasing process was observed.

It was proposed that the field-dependent dephasing is caused by coupling of the large electronic spin of Erbium to TLS modes of magnetic character. Magnetic TLS modes have also been considered in the field of glassy low-temperature physics, including dielectric echo experiments[18,19,20,21].

II. EXPERIMENTAL

We investigated a single-mode Er^{3+}-doped silicate glass fiber (ER 407 from INO, Canada), co-doped as follows: Er 0.07 at %, Al 2.65 at %, Ge 3.62 at %. The length of the fiber was 70 cm, corresponding to an optical depth of $\alpha L = 0.9$ at 1532 nm and 4 K. For measurements between temperatures of 10 K and 2.6 K the fiber was rolled around a copper cylinder (diameter = 4 cm) and fixed with adhesive tape to ensure a good thermal contact. The cylinder was fixed to the cold finger of a pulse tube cooler (Vericold Technologies). The Er^{3+}-doped fiber was fusion spliced to standard single-mode fibers, which were in good thermal contact with the cold finger. For measurements at temperatures lower than 2.6 K an identical fiber was installed in a similar setup in a home-built $^3He/^4He$ dilution refrigerator where it was cooled to temperatures down to 60 mK. A superconducting magnet inside this refrigerator enabled us to apply magnetic fields of up to 2 Tesla.

To measure the homogeneous linewidth Γ_h, or the corresponding decoherence time (lifetime) $T_2 = 1/\pi\Gamma_h$, over a wide range of temperatures and external magnetic fields, we performed both spectral hole burning and photon echo measurements[22]. The spectral hole burning technique directly yields the homogeneous linewidth, however, it is limited by laser frequency fluctuations during the measurement (in our case typically 0.5-1 MHz). Two-pulse photon echoes are generally more robust against laser frequency fluctuations, if the fluctuations are small compared to the frequency bandwidths of the optical pulses. The two-pulse photon echo technique is therefore the preferred approach for measuring homogeneous linewidths below 1 MHz (corresponding to more than a 318 ns decoherence time). However, decoherence times below approximately 100 ns are difficult to measure, as the requisite short pulses having sufficiently high peak intensities are difficult to obtain. In addition to these technical issues, spectral hole burning and two-pulse photon echo experiments often yield different decoherence times, as spectral diffusion[15,23] leads to an apparent time-dependent homogeneous linewidth. Spectral diffusion has a larger impact on the linewidth obtained by spectral hole burning, as such experiments are performed on a longer time scale than two-pulse photon echoes. The lifetime obtained by two-pulse photon echo experiments is often referred to as the intrinsic lifetime. To study decoherence over a wide range of times, the three-pulse photon echo technique can be used[23]. The experiments that we describe in this article employed all three of these techniques.

A. SPECTRAL HOLE BURNING EXPERIMENTS

To measure the homogeneous linewidth Γ_{hom} of a transition in an ensemble of inhomogeneously broadened absorbers, a laser having a frequency bandwidth small compared to the homogeneous linewidth is used to selectively excite ions, thereby creating a spectral hole in the absorption. Its width can be measured by scanning the laser frequency across its initial value and measuring the transmitted light intensity. Note that the *measurement pulse* is typically much weaker than the *excitation pulse.*
The output from an external-cavity diode cw laser (Toptica DL 100) was gated by two standard fiber-optic intensity modulators (Avanex SD 20 and IM10) in order to vary the laser intensity between excitation and measurement. The first modulator created the two pulses, whereas the second modulator suppressed the laser light between two consecutive excitation/measurement sequences. A Stanford delay generator (DG 535) triggered the sequence with a frequency of 10 Hz, the duration of the excitation pulse being typically 200 μs and the measurement time being typically 1 ms (short compared to the radiative lifetime of $\sim$10 ms). The light was then coupled into the Er^{3+}-doped fiber inside the refrigerator, and a fiber-coupled photodiode (NewFocus, mod. 2011v) detected the signal at the output of the refrigerator. Note that the whole setup relied on telecommunication fiber-technology.

B. PHOTON ECHO EXPERIMENTS

In a two-pulse photon echo (2PE) experiment, a first pulse, ideally a $\pi/2$ pulse, excites the atoms into a coherent superposition of the ground and excited state, forming an atomic coherence. With time, inhomogeneous broadening leads to rapid inhomogeneous dephasing. Application of a second pulse after a time t_{12}, ideally a π-pulse, reverses the inhomogeneous dephasing, thereby forming a photon echo a time t_{12} after the second pulse. The homogeneous dephasing, which cannot be reversed by the second pulse, leads to an exponential decay of the 2PE peak intensity as a function of t_{12}. A three-pulse photon echo (3PE) can be seen as an extension of a 2PE, where the second pulse is divided into two $\pi/2$-pulses, separated by a variable delay t_{23}. In a 3PE the first pulse creates an atomic coherence, but the second pulse transfers the coherence into a frequency-dependent population grating in the ground and excited states. The third pulse scatters off the grating, forming an echo a time t_{12} after the third pulse. In absence of spectral diffusion[15,23], the grating decays with the radiative lifetime T_1, approximately 10 ms in the case of Er^{3+} doped silicate fibers.
To perform 2PE (or 3PE) experiments, we used a setup

similar to the one employed in the SHB experiments. Two (or three) short pulses were created by the optical intensity modulators (IMs). The two IMs were synchronized and acted in series in order to have a good peak-to-background intensity ratio. The excitation pulses had durations of t_{2PE}=13 ns and t_{3PE}=20 ns, with a repetition frequency of 10 Hz. The pulses were then amplified by an optical amplifier (Variable Gain EDFA, Trillium Photonics, FAM C1725-A). In order to avoid excessive heating of the refrigerator due to amplified spontaneous emission from the amplifier, emitted between consecutive photon echo excitation sequences, we placed an additional IM between the optical amplifier and the input of the refrigerator. The photon echo was detected by a fast detector (IR DC-1 GHz, mod. 1611v, New Focus) after the refrigerator. The resulting peak powers were in the range of 100-200 mW at the refrigerator input. Owing to a good extinction of the background light (> 33 dB), the temperature could be stabilized at 150 mK and above.

III.   RESULTS

A.   SPECTRAL HOLE BURNING

We measured homogeneous linewidths by SHB at temperatures between 60 mK and 10 K, while applying different magnetic fields (B) ranging from 0 T to 2.2 T (see Fig. 1). All linewidths were extrapolated to zero excitation power, i.e. were corrected for power broadening effects[24]. Based on a large number of measurements we estimate the error to be of the order of 20 %. Without applied magnetic field, we observed a decreasing linewidth with decreasing temperature, following a $T^{1.4\pm0.1}$ power-law down to a temperature of 2 K (see Fig. 1 a dotted line). Below 2 K the linewidth reached a constant value of around 8-10 MHz, the slight variations being due to measurement errors.

In the case of an applied magnetic field of 1.3 T (see inset Fig. 2), the transmission spectrum showed not only one spectral hole at the frequency of the excitation pulse, but also two side holes equidistant from the central one. We found that the spectral hole separation was linearly dependent on the magnetic field (see Fig. 2), with a coefficient of 12.3 MHz/Tesla. We believe that this additional structure in the SHB spectra are so-called nuclear spin-flip sidebands caused by coupling between the total angular momentum of the Erbium and nuclear magnetic moments of nearby ^{27}Al ions[25]. Due to this superhyperfine, or ligand hyperfine interaction[26], optical transitions can also cause spin flips ($\Delta M = \pm1$) on a neighboring ion. Therefore one can expect to observe spectral side holes around the central hole. The observed splitting factor of 12.3±0.8 MHz/T can be linked to the ^{27}Al ion which has a gyromagnetic ratio of 11.1 MHz/T (for a free, unperturbed ion). The small difference can be attributed to an enhancement effect[27,28] in the silica network. Super-
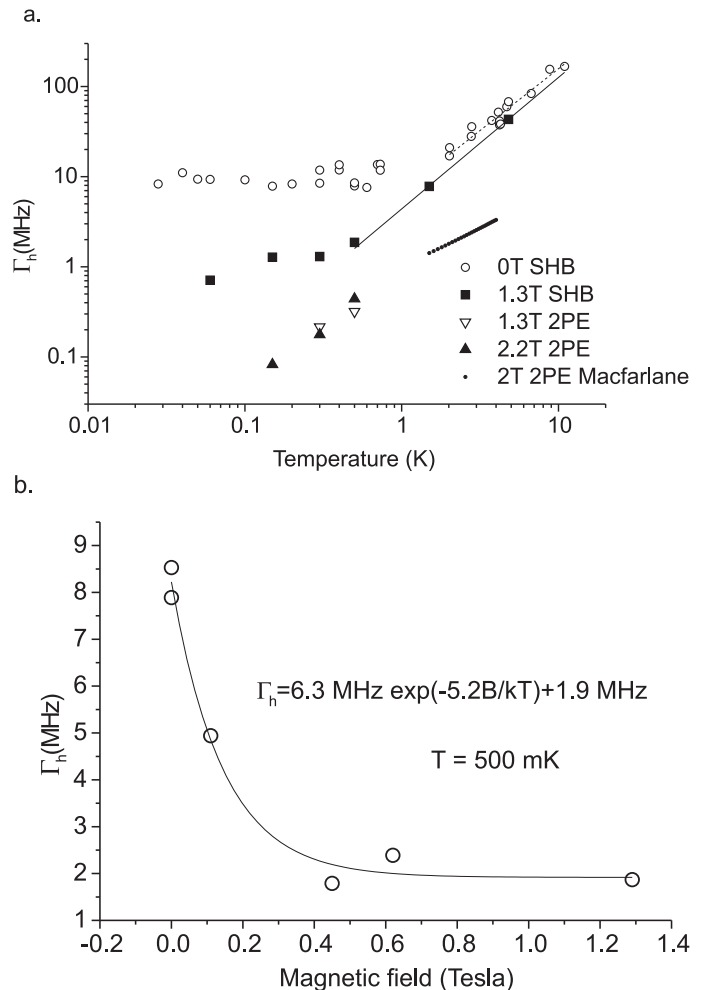

FIG. 1: a) Homogeneous linewidth of Er^{3+} as a function of temperature at different magnetic fields measured through spectral holeburning and photon echoes. For comparison the data obtained by Macfarlane et al.[17] is also plotted. b) Application of a variable external magnetic field at constant temperature of 500 mK leads to a strong decrease of the linewidth, reaching a saturated regime at a field of above one Tesla.

hyperfine splitting has also been observed in other Er^{3+}-doped inorganic crystals, eg. $YAlO_3$ (Er-^{27}Al), $YLiF_4$ (Er-^{7}Li,^{19}F), and LaF_3 (Er-^{19}F) (see Ref.[25]).

The homogeneous linewidth at a magnetic field of 1.3 T, measured from the spectral hole at the excitation frequency, showed a temperature dependence similar to that at $B = 0$ (see Fig. 1a). However, the linewidth continued to decrease according to a $T^{1.5\pm0.1}$ law down to around 500 mK (solid line). The measurements at temperatures below 500 mK must be interpreted with some caution, as laser frequency fluctuations during the excitation and measurement are likely to play a significant role. Figure 1b shows the homogeneous linewidths measured at a temperature of 500 mK as a function of applied magnetic field. We observed a significant decrease of the linewidth for increasing B field, from 8.2 MHz to a level of saturation of 2.2 MHz. Note that the analysis of the mea-
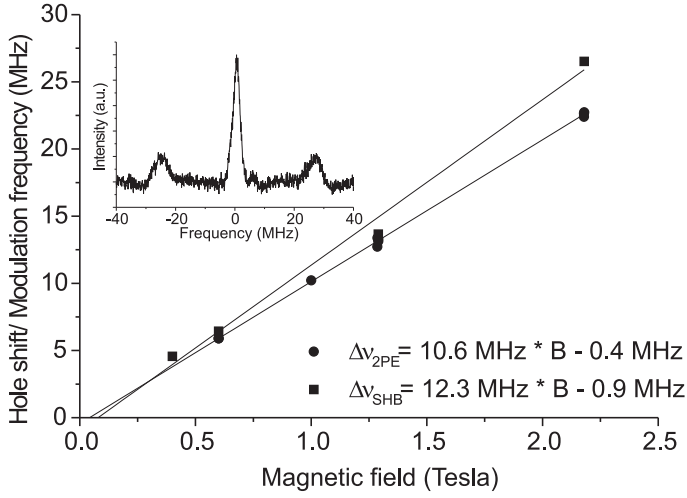
FIG. 2: The modulation frequency of the 2PE decay curve, and the separation between the central spectral holes and the side holes measured with SHB as a function of magnetic field. Inset: Spectral hole burning spectrum in Er^{3+} silicate at a magnetic field of 1.28 T and a temperature of 60 mK.
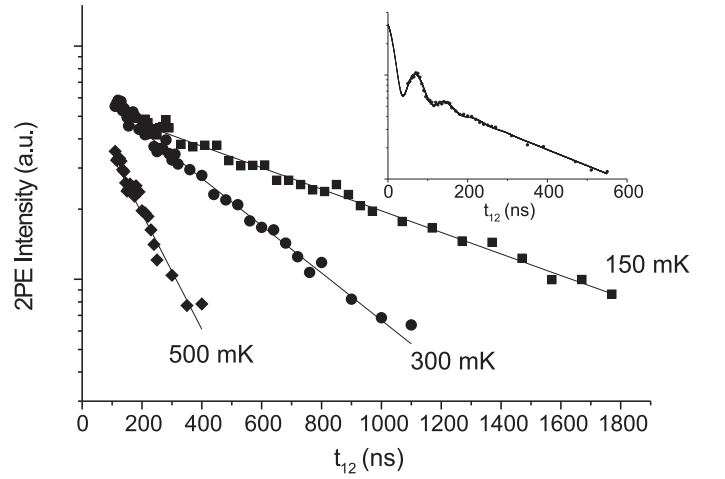

FIG. 3: Two-pulse photon echo peak intensity as a function of time delays between the two excitation pulses for different temperatures. Inset: For short time delays a magnetic field dependent modulation was observed.

surements at intermediate magnetic fields ($0 < B < 0.6$ T) was difficult, due to the three, partly overlapping, spectral holes. We found similar, strong magnetic-field dependence of the homogeneous linewidth at other temperatures below 4 K.

B. PHOTON ECHOES

To measure the intrinsic T_2 homogeneous lifetime, we performed 2PE experiments at three sub-Kelvin temperatures, 150 mK, 300 mK and 500 mK and applied magnetic fields of 0.6 T, 1.3 T and 2.2 T. In general, one expects to observe a simple exponential decay of the 2PE peak intensity when varying the time t_{12} between the two excitation pulses. The associated decay time τ is directly connected to the lifetime through the relation $T_2 = 4\tau$. In all our 2PE measurements, however, we observed strong sinusoidal modulations during the first 100-200 ns of the decay curve (see inset of Fig. 3). These modulations can be explained by coherent excitations of several transitions in the atoms, as has been observed previously[29,30,31,32]. Although the small number of modulations visible in our experiments did not allow us to fit the data to the models proposed in[30], we could extract the main modulation frequency. As shown in Fig. 2, it depends linearly on the magnetic field with a coefficient of 10.6±0.1 MHz/T. This value is in close agreement with the value measured from the spectral hole splitting, 12.3±0.8 MHz/T, leading to the conclusion that the modulation observed with 2PE and the splitting found with SHB have a common origin. Note that similar modulations have been observed in $Er:Y_2SiO_5$ due to coupling between the Er^{3+} ion and neighboring ^{89}Y ions[33]. The

inset of Fig. 3 shows that the modulation is strongly damped, which can be explained by taking into account site-to-site inhomogeneities in the frequencies of the spin-flip sidebands[31,32].

As the modulation of the decay curves disappeared for times t_{12} longer than 200 ns, we used a simple exponential fit to compute the decay times based on these data, as shown in Fig. 3 for a magnetic field of 2.2 T. We observed a strong dependence of the decay time on the temperature, yielding lifetimes of $T_2 = 760\pm80$ ns, 1710±60 ns and 3760±140 ns at temperatures of 500 mK, 300 mK and 150 mK, respectively. The stated errors refer to two standard deviations, as obtained from the exponential fit. Measurements with a magnetic field of 1.3 T and 0.6 T led to similar results. The corresponding linewidths at 1.3 T and 2.2 T are shown in Fig. 1. Extrapolating these data points to higher temperatures and comparing them to the SHB measurements at 1.3 T, we find a similar temperature dependence. Yet, the linewidths obtained through 2PE are significantly smaller (by a factor of 6 at a temperature of 4 K). This result can be attributed to spectral diffusion that leads to a time-dependent line broadening. Note that the SHB measurements below 500 mK are likely to be influenced by laser frequency fluctuations, as mentioned above, and should therefore be interpreted with some caution.

In order to investigate the role of spectral diffusion, we performed 3PE measurements. The effect of spectral diffusion on the 3PE process is to reduce the modulation depth in the population grating by "smearing" it out in frequency space, thus reducing the efficiency of the echo formation. In Fig. 4 the 3PE peak intensity is plotted as a function of the delay time t_{23} between the second and the third pulse, while the distance between the first two pulses was kept constant at t_{12}=50 ns. A fast decay was observed for t_{23} shorter than 200 μs, and a much
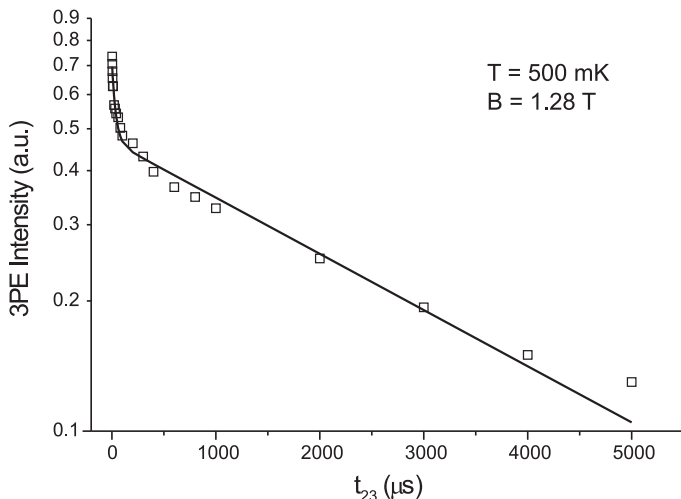
FIG. 4: Stimulated three-pulse photon echo peak intensity as a function of delay time between the second and the third pulse at a magnetic field of 1.28 T and a temperature of 500 mK.

slower decay for longer t_{23}. As the excited state lifetime is around 10 ms, much longer than the observed fast decay, this measurement clearly indicates that spectral diffusion plays an important role on a microsecond timescale. After 200 μs, however, the spectral diffusion reaches a maximum (corresponding to a time-independent homogeneous linewidth), and the 3PE peak intensity relaxes with a time constant of around 7 ms, approximately equal to the excited state lifetime of around 10 ms. A similar behavior has been observed previously by Broer et al.[15] in 3PE experiments with a Nd^{3+}-doped silica fiber.

IV. DISCUSSION

The temperature dependence of the homogeneous linewidth measured by SHB at temperatures above 2 K with zero magnetic field, and above 0.5 K and 1.3 Tesla follows a power-law of $T^{1.4}$ and of $T^{1.5}$, respectively (see Fig. 1a). This can be explained assuming coupling of the Erbium impurities to TLS modes[14], that in turn are interacting with the phonon bath. Flipping of a TLS through phonon interaction leads to a change in the optical transition frequency of the neighboring RE-ions, resulting in an optical dephasing. Assuming the standard approximations in existing models to be correct[16] the temperature dependence for an electric dipole-dipole interaction between the TLS and the RE-ion should be of the form $\Gamma_{TLS}^0 = aT^{(1+\mu)}$. Here, μ describes the energy dependence of the TLS density of states: $\rho(E) \sim E^{\mu}$. The temperature dependence we found is similar to results previously obtained through 2PE measurements in an Er^{3+}:silicate fiber ($\Gamma_h \propto T$)[17] and in a Nd^{3+}:silica fiber ($\Gamma_h \propto T^{1.3}$)[15], respectively. The differences can be explained by a different glass composition, by the use of

a different RE-ion, as has been suggested by[34], or by the use of 2PE measurements as compared to our SHB measurements.

The aforementioned model predicts a decrease of linewidth down to arbitrarily small values when decreasing the temperature. In contrast to this, our measurements without applied magnetic field clearly showed the existence of a temperature independent linewidth below 2K (see Fig. 1). Surprisingly, application of a magnetic field allowed us to reduce the linewidths by 8-10 MHz. The relative narrowing is particularly pronounced at temperatures below 2K, but was also observed at a temperature of 4K. Although a similar, however less pronounced effect is known to exist in RE crystals[35,36], this behavior has only very recently been observed in a glass by Macfarlane et al.[17]. The field-dependent narrowing cannot be explained by standard models of coupling of the RE-ion to TLS modes. Furthermore, as has been pointed out in[17] this effect is not likely to originate from magnetic dipole-dipole interaction between Er^{3+} ions, as is typical in Er^{3+}-doped inorganic crystals[35,36], since the contribution from spin-spin interactions is only of the order of 100 kHz at similar Er^{3+} concentrations. Macfarlane et al. instead proposed that the large electronic spin of Er^{3+} ions couples to TLS modes having a magnetic character. To describe the magnetic-field dependent dephasing the authors used a phenomenological thermal activation law

$$\Gamma_h(B,T) = \Gamma_{TLS}^0(T) + \Gamma_{TLS}^1 exp(-g_{eff}\beta B/kT) \quad (1)$$

where B is the magnetic field, β the Bohr magneton, g_{eff} an effective g factor of the spin system and Γ_{TLS}^0 the magnetic field independent TLS part defined above. Fitting this expression to the homogeneous linewidths in Fig. 1b, we obtained $g_{eff} = 5$ (at 500 mK), similar to the value of g_{eff}=3.2 given in[17]. The general features of the magnetic field dependent linewidth (Fig. 1b) correspond well to the fitted curve. However, due to difficult-to-resolve, partly overlapping spectral holes at intermediate fields, we estimate the error in g_{eff} to be around 50%.

Our results confirm the recent observation of a strongly field-dependent, optical dephasing mechanism in RE-ion-doped glasses and can support the hypothesis of magnetic TLS modes. Note that the magnetic character of TLS modes has also been proposed to explain unusual magnetic field dependent dielectric properties of glasses as observed through dielectric polarization echoes[19,20,21]. Nevertheless, we would like to point out the possibility that clustering effects in Er^{3+} doped glasses[37,38] might also contribute to the magnetic-field dependent dephasing. Clustering leads to increased local Er^{3+} ion concentrations and thereby to enhanced spin-spin interactions as compared to crystals with similar mean ion concentration. Erbium clustering is generally reduced by codoping with Aluminium[38]. Yet, the only naturally abundant isotope of Aluminium has a strong nuclear spin and is known to cause strong dephasing in RE-ion-doped inorganic crystals[23]. It

would thus be interesting to study the optical dephasing in fibers having different Erbium concentration, as well as different concentrations of co-dopants such as Germanium, Aluminium and Lanthanum.

The homogeneous lifetimes (or linewidths) that we measured via 2PE experiments at 0.6 T and above did not show a magnetic-field dependence, suggesting that a saturation limit was reached for the temperatures studied (150 mK, 300 mK and 500 mK). This is consistent with the SHB measurements as a function of magnetic field (see Fib. 1b). It should be noted, that extrapolating our 2PE results to temperatures between 1.5 and 4K yields homogeneous linewidths of the same order of magnitude as observed by Macfarlane et al.[17] (see Fig. 1a). Yet, in order to compare the coherence properties of Erbium in the two fibers having slightly different glass composition, measurements at the same temperature would be required.

An interesting feature of our investigations is the large difference in homogeneous linewidths measured by 2PE as compared to the SHB-technique. Due to the resolution limit imposed by laser frequency fluctuations, this is best exemplified at 500 mK and 1.3 T, where the 2PE and SHB measurements yielded 0.4±0.04 and 1.6±0.3 MHz, respectively. Note that the second value is corrected for laser frequency fluctuations. As mentioned earlier we believe the difference to be due to spectral diffusion, or more precise spin diffusion, as qualitatively confirmed by the 3PE measurements shown in Fig. 4. To quantify the impact of spin diffusion on the homogeneous linewidth, we analyzed the 3PE data, taken at 500 mK and 1.3 T, using a spin-diffusion model previously employed by Böttger *et al.*[35] The 3PE peak intensity can then be described by the expression

$$I(t_{12}, t_{23}) \sim e^{-2t_{23}/T_1} e^{-4\pi t_{12}\Gamma_h(t_{23})} \qquad (2)$$

where t_{12} is the time difference between the first two pulses, t_{23} the delay between the second and the third pulse, and T_1 is the excited state relaxation lifetime. In this model the homogeneous linewidth is expressed as the sum of the intrinsic part Γ_0 and a part dependent on spectral diffusion, acting during t_{23} and contributing maximally $\Gamma_1/2$:

$$\Gamma_h(t_{23}) = \Gamma_0 + \frac{1}{2}\Gamma_1[1 - e^{-Rt_{23}}]. \qquad (3)$$

Here, R is the rate with which spectral diffusion takes place. Note that this spectral diffusion model yields a homogeneous linewidth (in the limit $Rt_{23} \gg 1$) of $\Gamma_0 + \Gamma_1$ if measured through SHB[35]. Fitting the 3PE peak intensities to this model (see Fig. 4) we obtained Γ_1=1.3±0.1 MHz, R=0.026±0.005 μs^{-1} and T_1=6.7±0.5 ms. If the 2PE experiment is taken to yield the intrinsic homogeneous linewidth $\Gamma_0 = 0.4$ MHz, we can estimate the SHB linewidth to be Γ_{hom}=0.4+1.3=1.7±0.1 MHz. This value is in surprisingly close agreement with the linewidth of 1.6±0.3 MHz that we measured by SHB, supporting the previous conclusion that spectral diffusion can explain the difference between the SHB and 2PE results.

We conclude this discussion by comparing our results with other measurements carried out in Er^{3+}-doped as well as in other RE-ion-doped glasses. SHB measurements on various RE-ions in different host materials have generally resulted in larger homogeneous linewidths as compared to what is presented in this article (see Fig. 1a). For instance, a linewidth of 106 MHz was measured in a Er^{3+}-doped fluorozirconate glass at 1.6 K[39]. In a Eu^{3+}-doped and a Pr^{3+}-doped silicate glass, linewidths of 24 MHz (1.6 K) and 318 MHz (2 K) were measured[40], respectively. The large differences between all these results, including ours, can be explained by the presence, or absence, of an applied magnetic field, different RE-ion concentrations, different glass compositions, and spectral diffusion.

Only few investigations of optical dephasing times through 2PE have been reported. The 3.8 μs lifetime that we observed in an Er^{3+}-doped silicate fiber at 150 mK and 2.2 T is, to the best of our knowledge, the longest lifetime measured so far. Macfarlane et al.[17] recently obtained a lifetime of 230 ns, at 1.6 K and 3 Tesla, using a similar Er^{3+}-doped silicate fiber. A homogeneous lifetime of 1.6 μs has been found in a Nd^{3+}-doped silica fiber at 100 mK[15]. Surprisingly, no magnetic field was necessary to obtain this long lifetime, although Neodymium has an unquenched electronic spin when doped into a silica glass and therefore strong magnetic interactions. However, we would like to stress that the fiber was very weakly doped with Nd^{3+} and had no other co-dopants. These results indicate that the RE-ion concentration and the presence and concentration of co-dopants could have an impact on the magnetic-field dependent dephasing.

V. CONCLUSIONS

We have presented investigations of optical coherence properties of an Er^{3+}-doped silicate fiber. Our findings reveal a strong magnetic-field dependent optical dephasing effect that has been discovered only very recently[17]. It is likely that the effect is linked to tunnelling modes, specific to amorphous systems, which seem to obtain a magnetic character. For further elucidation more experimental studies (e.g. spectral holeburning, photon echo and dielectric echo experiments on fibers having different co-dopants, RE-ions and concentrations) as well as sound theoretical studies would be important. Our investigations also revealed, for the first time in fibers, a superhyperfine structure, which we believe to be due to interaction of Er^{3+} ions with neighboring ^{27}Al nuclei.

The fact that μs coherence times can be achieved at sub-Kelvin temperatures through application of a magnetic field is promising for proposals using coherent control of ensemble of ions. For instance, this would allow for the building of a source of single photons on demand, based on storage and deterministic recall of a heralded

single photon[41], and a proof-of-principle demonstration of a quantum memory based on the CRIB protocol. Furthermore, the coherence time is sufficiently long to transfer the optical coherences, after absorption of a photonic quantum state, into superpositions of different ground states with increased coherence times, thereby increasing the storage time. The application of a magnetic field also leads to a separation of the superhyperfine levels as required for the preparation of a single, homogeneously broadened, absorption line on a non-absorbing background with sufficiently large frequency bandwidth. In order to increase the bandwidth beyond the limit set by the Er^{3+}-^{27}Al superhyperfine structure, it should also be possible to use a fiber consisting of a pure Er^{3+}-doped silica core surrounded by depressed index cladding, provided the additional levels originate from the presence of ^{27}Al ions.

In conclusion, together with the recent demonstration of controlled broadening of a transient spectral hole in an identical fiber[42] and the possibility to achieve arbitrary large optical depths, our results demonstrate the potential of Er^{3+}-doped optical fibers, and RE-doped fibers in general, for CRIB based quantum state storage.

[1] T. W. Mossberg, Opt. Lett. **7**, 77 (1982)

[2] M. Mitsunaga, Optical and Quantum Electronics **24**, 1137 (1992)

[3] S. Kröll and U. Elman, Opt. Lett. **21**, 1834 (1993)

[4] Quantum Computation and Quantum Information, M. A. Nielsen and I. L. Chuang , Cambridge UK (2000)

[5] G. J. Pryde, M. J. Sellars, and N. B. Manson, Phys. Rev. Lett. **84**, 1152 (2000)

[6] N. Ohlsson, R. K. Mohan, S. Kröll, Opt. Comm. **201**, 71 (2002)

[7] H. J. Briegel, W. Dur, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **81**, 5932 (1998)

[8] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, Rev. Mod. Phys. **74**, 145 (2002)

[9] B. Kraus, W. Tittel, M. Nilsson, S. Kröll, N. Gisin J. I. Cirac, Phys. Rev. A **73** 020302(R) (2006)

[10] A. L. Alexander, J. J. Longdell, M. J. Sellars, and N. B. Manson, Phys. Rev. Lett. **96**, 043602 (2006)

[11] M. Nilsson and S. Kröll, Opt. Commun. **247**, 393 (2005)

[12] Note that the memory time can be extended beyond the optical coherence time by temporarily transferring the optical coherences to coherences between different ground state (hyperfine)-levels having longer coherence times.

[13] P. B. Sellin, N. M. Strickland, T. Böttger, J. L. Carlsten, and R. L. Cone, Phys. Rev. B **63**, 155111 (2001)

[14] D. L. Huber and M. M. Broer and B. Golding , Phys. Rev. Lett. **52**, 2281 (1984)

[15] M. M. Broer, B. Golding, W. H. Haemmerle, and J. R. Simpson , Phys. Rev. B **33**, 4160 (1986)

[16] E. Geva and J. L. Skinner, J. Chem. Phys. , **107**, 7630 (1997).

[17] R. M. Macfarlane, Y. Sun, P. B. Sellin, and R. L. Cone, Phys. Rev. Lett. **96**, 033602 (2006)

[18] N. Vernier and G. Bellessa, Phys. Rev. B **48**, 12842 (1993)

[19] S. Ludwig, C. Enss, P. Strehlow, and S. Hunklinger, Phys. Rev. Lett. **88**, 075501 (2002)

[20] A. Würger, A. Fleischmann, and C. Enss, Phys. Rev. Lett. **89**, 237601 (2002)

[21] A. Akbari and A. Langari, Phys. Rev. B **72**, 024203 (2005)

[22] R. M. Macfarlane and R. M. Shelby, Coherent transients and holeburning spectroscopy in rare earth ions in solids, in: A. A. Kaplyankii and R. M. Macfarlane (Ed.), Spectroscopy of solids containing rare-earth ions, vol. 21, Elsevier Science Publishers, Amsterdam Netherlands (1987).

[23] R. Yano, M. Mitsunaga, and N. Uesugi, Phys. Rev. B **45**, 12752 (1992)

[24] E. S. Maniloff, F.R. Graf, H. Gygax, S. B. Altner, S. Bernet, A. Renn, U. P. Wild , Chem. Phys. **193**, 173-180 (1995)

[25] R. Wannemacher, R. M. Macfarlane, Y. P. Wang, D. Sox, D. Boye and R. S. Meltzer, Journal of Lumniescence **48,49**, 309 (1991)

[26] A. Abgram and B. Bleaney, Electronic Paramagnetic Resonance of Transition Ions, Clarendon Press, Oxford UK(1970)

[27] R. M. Macfarlane, D. P. Burum, and R. M. Shelby, Phys. Rev. B **29**, 2390 (1984)

[28] R. M. Macfarlane, and R. M. Shelby, Opt. Lett. **6**, 96 (1981)

[29] E. A. Whittaker and S. R. Hartmann, Phys. Rev. B **26**, 3617 (1982)

[30] M. Mitsunaga, R. Yano, and N. Uesugi, Phys. Rev. B **45**, 12760 (1992)

[31] M. K. Kim, R. Kachru, Phys. Rev. B **40**, 2082 (1989)

[32] M. K. Kim, R. Kachru, Phys. Rev. B **44**, 9826 (1991)

[33] R. M. Macfarlane, T.L. Harris, Y. Sun, and R. L. Cone, R. W. Equall, Opt. Lett. **22**, 871 (1997)

[34] Th. Schmidt, J. Baak, D. A. van de Straat, H.B. Brom, and S. Völker, Phys. Rev. Lett. **71**, 3031 (1993)

[35] T. Boettger, Y. Sun, C. W. Thiel, and R. L. Cone, Advanced Optical Data Storage, Conference 4998, Photonics West, San Jose, CA USA (2003)

[36] R. M. Macfarlane, and R. M. Shelby, Opt. Comm. **42**, 346 (1982)

[37] C. C. Robinson, Journal of Non-Crytaline Solids, **15**, 11 (1974)

[38] B. J. Ainsle, Journal of Lightwave Technology, **9**, 220 (1991)

[39] L. Bigot, S. Choblet, A.-M. Jurdyc, and B. Jacquier, and J.-L. Adam, J. Opt. Soc. Am. B **21**, 307 (2004)

[40] R. M. Macfarlane and R. M. Shelby, Opt. Comm. **45**, 46 (1983)

[41] S. Fasel, O. Alibart, S. Tanzilli, P. Baldi, A. Beveratos, N. Gisin, and H.Zbinden, New J. Phys., **6**, 163 (2005)

[42] S. R. Hastings-Simon, M. U. Staudt, M. Afzelius, P. Baldi, D. Jaccard, W. Tittel, N. Gisin, submitted quant-ph/0603194